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The implications of climate change for the water environment in England

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Abstract

This paper reviews the implications of climate change for the water environment and its management in England. There is a large literature, but most studies have looked at flow volumes or nutrients and none have considered explicitly the implications of climate change for the delivery of water management objectives. Studies have been undertaken in a small number of locations. Studies have used observations from the past to infer future changes, and have used numerical simulation models with climate change scenarios. The literature indicates that climate change poses risks to the delivery of water management objectives, but that these risks depend on local catchment and water body conditions. Climate change affects the status of water bodies, and it affects the effectiveness of measures to manage the water environment and meet policy objectives. The future impact of climate change on the water environment and its management is uncertain. Impacts are dependent on changes in the duration of dry spells and frequency of 'flushing' events, which are highly uncertain and not included in current climate scenarios. There is a good qualitative understanding of ways in which systems may change, but interactions between components of the water environment are poorly understood. Predictive models are only available for some components, and model parametric and structural uncertainty has not been evaluated. The impacts of climate change depend on other pressures on the water environment in a catchment, and also on the management interventions that are undertaken to achieve water management objectives. The paper has also developed a series of consistent conceptual models describing the implications of climate change for pressures on the water environment, based around the source-pathway-receptor concept. They provide a framework for a systematic assessment across catchments and pressures of the implications of climate change for the water environment and its management.

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climate change, water quality, river flows, groundwater, estuaries, lakes, water framework directive

I Introduction

Across many parts of the world the water environment is facing increasing challenges. Loadings of nutrients have increased significantly, air pollution has caused surface water acidification, a wide variety of pollutants are discharged to water courses and abstractions from rivers and groundwater have affected flow regimes. As of 2009, only 44% of rivers in the 27 member states of the European Union, plus Norway, were classified as being of 'good' or 'high' ecological status (European Commission, 2012), and in some regions less than 10% of rivers met this standard. However, water managers are well aware of these pressures, and have implemented improvement measures. For example, whilst 4% of rivers and lakes in Saxony, Germany, were classified as being of good status in 2009, by 2015 it is anticipated that this will increase to 14% (Spanhoff et al., 2012). Climate change poses an additional challenge. It has the potential to affect the water environment through changes to water quantity and quality and freshwater biodiversity, and to influence the effectiveness of management measures required to restore water quality. A major assessment of the probable impact of climate change on European lakes, rivers and wetlands has been conducted recently (Kernan et al., 2010) and George (2010) examined the potential impact of climate change on the nutrient status of European lakes, but a thorough systematic study of the impact of climate change on the water environment in England has yet to be carried out.

This paper presents a high level review of the potential consequences of climate change for the water environment in England, with a particular emphasis on implications for the delivery of water management objectives. It is based on a review of published literature produced for the Department for Environment, Food and Rural Affairs (Defra) (Arnell et al., 2014a), and combines evidence from published case studies with scientific first principles. A significant amount of work has been done and published. Many processes are understood in principle if not adequately captured by models but, as the review shows, there are substantial gaps. In particular, studies have been undertaken in a relatively small subset of environments and it is therefore difficult to generalise to produce national-scale assessments. This paper summarises the current knowledge of potential impacts in England, and proposes a series of conceptual models to frame future catchment or national-scale assessments. It develops the review produced by Whitehead et al. (2009a) by considering all types of water bodies, by considering potential impacts from first principles and observations as well as model results, by explicitly considering implications for water management and finally by proposing generalised conceptual models.

II The water environment: current and future pressures

Managing the water environment

The dominant driver for the management of the water environment in England, and indeed the rest of the European Union (EU), is the Water Framework Directive (WFD: 2000/60/EC), adopted in 2000. This drew together a number of previous directives, and its primary objective is to provide 'good' status for all European water bodies by set deadlines (2015, 2021 or 2027 depending on affordability and feasible system recovery times).

'Good' is interpreted in terms of ecological and chemical status, and the status of designated 'protected areas'. These designated protected areas consist of drinking water protected areas (DrWPAs), nutrient sensitive areas (nitrate vulnerable zones and areas downstream of urban waste water treatment sites), shellfish waters, bathing waters, and sites with unique and valuable habitats (Natura2000 sites). WFD objectives are delivered through periodic river basin management plans (RBMPs), which specify actions (known as the 'programme of measures') to be taken by a wide range of stakeholders. The first round of RBMPs was published in 2009, and the second round is due to be produced by the end of 2015. Water managers also have a duty to reduce pollution from specified substances to surface water and groundwater to maintain regulatory standards. They also have an operational responsibility to respond to, and reduce risks from, individual polluting incidents.

The water environment comprises both surface and groundwater bodies. Surface water bodies are rivers, lakes, transitional waters and coastal waters. Transitional waters are bodies of surface water in the vicinity of river mouths which are partly saline but substantially influenced by freshwater flows; most are estuaries and rias, but there are some coastal lagoons. Coastal waters are within one nautical mile of the coast, and can therefore be affected by inflows of surface and groundwater from the land, typically from small catchments (because the largest rivers enter the sea through estuaries). More broadly, the 'water environment' is often interpreted to include those terrestrial ecosystems which are influenced by the volume and quality of water, largely because the interventions which may be necessary to maintain their status come through water management. This paper focuses on surface and groundwater bodies, and does not consider explicitly water-dependent terrestrial ecosystems such as wetlands.

The regulatory policy drivers are summarised in Table 1. Most are focused around the definition of the status of a water body, based on a very wide range of chemical, biological and, for groundwater bodies, quantitative indicators (there are dozens of chemical indicators, although not all are measured or relevant for each water body). Threshold values are defined separately for each indicator based either on values deemed to be indicative of 'good' status (based on observations), or on toxicological limits. Different threshold values may be defined for different types of water body (river, lake, etc.), and for different categories of each water body type. Quantitative indicators are not defined for the Natura2000 sites because of their diversity, and status is based on expert judgement. In all these cases, the aims of water management are to allow water bodies to maintain or achieve a defined status, to prevent deterioration and, for groundwater bodies, reverse significant adverse trends. Compliance is therefore measured in terms of the water body status. The regulatory approach for nutrient sensitive zones is slightly different. In these cases, 'sensitive areas' are defined on the basis of chemical and biological indicators, and specific management approaches must be implemented in these areas (for example, relating to the application of nitrogen by farmers and the treatment of sewage effluent). Compliance under these regulations is measured in terms of the implementation of these interventions, not in terms of the quality of the receiving water – although this will typically be addressed by the other regulations.

Current pressures on the water environment in England

There are seven main current pressures on the water environment in England, and Table 2 maps these onto the regulatory framework in Table 1:

Table 1. Regulatory policies affecting the water environment in England.

Policy instrument	Reference	Description
Water Framework Directive (WFD)	2000/60/EC	Defines status of surface water bodies in terms of ecological status (biological and physico-chemical status) and chemical status (specific chemicals). Defines status of groundwater bodies in terms of quantity and chemical quality
Marine Strategy Framework Directive (MSFD)	2008/56/EC	Defines status of marine waters in terms of qualitative descriptors covering ecology, chemistry and the physical environment
Protected areas		
Drinking water protected areas (DrWPAs)	Article 7, WFD	Defines status on basis of specific chemical determinands: a DrWPA is 'at risk' if treatment is needed to meet drinking water standards
Shellfish waters	Shellfish Directive 2006/113/EC; under WFD from 2014	Define status on basis of specific chemical and microbial determinands
Bathing waters	Bathing Waters Directive 2006/7/EC	Define status on basis of specific microbial determinands
Nutrient sensitive zones: nitrate vulnerable zones (NVZs)	Nitrates Directive 91/676/EC	NVZs based on nitrate concentrations; specific management actions necessary within NVZs
Nutrient sensitive zones: urban waste water treatment	Urban Waste Water Treatment Directive 91/276/EEC	Sensitive waters based on eutrophication risk or nitrate concentrations, and include designated shellfish and bathing waters; specific management actions necessary within sensitive waters
Natura2000	Habitats Directive 92/43/EEC	Water-dependent ecosystems, sensitive to changes in water volume or quality. Objective is to maintain status
Pollution control		
Priority substances	WFD Article 16, Annex X substances, as defined in Environmental Quality Standards Directive 2008/105/EC	Define status on basis of 33 specific chemical determinands
Groundwater pollution	Groundwater WFD Daughter Directive 2006/118/EC	Define status on basis of pesticides, nitrate, salinity and specific chemical determinands

Table 2. Relationship between pressures on the water environment and regulatory policies.

	Nutrient enrichment and eutrophication	Organic enrichment	Pollution from organic contaminants and toxic chemicals	Acidification	Over-abstracftion from rivers and groundwater	Invasive species
Water Framework Directive						
Marine Strategy Framework Directive						
Drinking water protected areas						
Shellfish waters						
Bathing waters						
Nitrate vulnerable zones						
Urban waste water treatment						
Natura2000 sites						
Pollution from priority substances						
Groundwater pollution						

- eutrophication and nutrient enrichment (primarily due to nitrogen and phosphorus species);
- organic pollution leading to increased oxygen demand from species inhabiting freshwater habitats (organic enrichment);
- pollution from organic contaminants (including pesticides, herbicides and microbial pathogens) and toxic chemicals;
- acidification (from sulphur and nitrogen deposition and their legacies);
- over-abstraction from rivers and groundwater;
- morphological changes to water bodies (erosion, sedimentation and channel modification);
- invasive species affecting species interactions and biodiversity.

As of 2013, 21% of rivers, 26% of lakes, 16% of transitional waters and 33% of coastal waters in England were classified as having 'good' ecological status under the WFD, and in 2010

38% of groundwater bodies were classified as having good status. Most of the rivers that fail to achieve good ecological status do so largely because of excessive nutrients (mostly phosphorus concentrations) adversely affecting biological communities, morphological modifications to the river channel (such as obstructions to fish movement) and sedimentation affecting fish and invertebrate communities. Eutrophication and excess nutrients are also the dominant causes for lakes, transitional and coastal waters failing to achieve good ecological status. The groundwater bodies that fail to achieve good status do so for a combination of reasons including eutrophication (particularly high nitrate concentrations) and also because over-abstraction affects the volume of surface waters.

Around 30% of the surface water DrWPAs in England and Wales, and 70% of groundwater DrWPAs were classified as 'at risk' in 2013 because additional treatment may be needed to meet drinking water standards (Environment Agency, 2013a). The dominant reasons for 'at risk' status for surface water DrWPAs are excessive pesticide concentrations, poor water colour (due to high dissolved organic carbon) and high algal concentrations due to excessive nutrients. High nitrate concentrations are by far the main reason why groundwater DrWPAs are at risk (Environment Agency, 2013a). Virtually all of England's bathing and shellfish waters meet basic quality standards, but only 81% and 34%, respectively, meet the stricter 'guideline' standards. All these failures are due to excessive faecal coliform concentrations.

Failure to achieve target status is therefore due to a variety of drivers, mostly ultimately related to various dimensions of water chemistry. Excessive concentrations of nutrients and pollutants derive from both point and diffuse sources.

Climate change

By 2050, mean winter temperatures in England are projected to rise by approximately 1.1 to 3.2°C (with a central estimate of 2.1°C) and mean summer temperatures could be 1.2 to 4.2°C (central estimate 2.5°C) higher than in 1961to 1990 (UKCP09: Murphy et al., 2009). Mean winter precipitation could increase by 2 to 28% (central estimate 13%) and mean summer precipitation could change by between −36% and +4% (central estimate −16%). Table 3 shows the variation in the potential impact on average seasonal temperature and precipitation across England, and illustrates the large amount of uncertainty even assuming one scenario for future emissions. The frequency of intense rainfall events is likely to increase, as a warmer atmosphere can hold more water. Warmer and drier conditions *on average* during summer could be expected to lead to more frequent hot dry summers.

Sea level is projected to rise by approximately 18–26 cm by 2050 (relative to 1990) in south-east England, and sea surface temperatures to increase by of the order of 0.2–0.3°C per decade (suggesting an increase of 1.6–2.4°C by 2050 relative to 1961–1990). The salinity of the seas around England is likely to reduce by 2050, particularly in the North Sea, but changes in estuaries will be strongly affected by changes in river flows. Stratification in estuaries is likely to increase slightly, and the duration of stratification in summer to increase (Statham, 2012). There is currently considerable uncertainty on potential changes in the circulation in the coastal zone.

Other pressures on the water environment

By the mid-2030s, the population of England is projected to increase by between 6.5 and 9.6 million over the 2012 level (Office of National Statistics, 2013). This will have two effects on the water environment. First, demand for water resources will likely increase, although the effect will depend on future per capita water use; the Environment Agency (2013b) projects changes in demand in England and Wales by 2050 under different scenarios ranging from a decrease of 28% to an increase of 49% (relative

Table 3. UKCP09 climate change projections for the 2050s, assuming medium emissions (mean is shown with 10th and 90th percentile in brackets). The change is relative to the 1961–1990 mean.

	Temperature (°C)		Precipitation (%)	
Region	Winter	Summer	Winter	Summer
East of England	2.2 (1.1–3.4)	2.5 (1.1–3.9)	14 (1–24)	−16 (−36–1)
London	2.2 (1.1–3.4)	2.7 (1.2–4.2)	14 (2–29)	−19 (−36–6)
North-east of England	2.0 (1.0–3.0)	2.5 (1.2–4.1)	11 (3–26)	−15 (−36–1)
North-west of England	1.9 (1.1–3.1)	2.6 (1.2–4.1)	13 (1–24)	−18 (−30–1)
South-east of England	2.2 (1.2–3.2)	2.3 (1.2–4.4)	11 (2–27)	−19 (−37–6)
South-west of England	2.1 (1.1–3.4)	2.7 (1.1–3.9)	17 (1–24)	−20 (−36–1)
West Midlands	2.1 (1.1–3.2)	2.6 (1.3–4.6)	13 (4–38)	−17 (−42–7)
Yorkshire and Humber	2.2 (1.2–3.5)	2.3 (1.3–4.6)	11 (2–32)	−19 (−41–7)
Average	**2.1 (1.1–3.3)**	**2.5 (1.2–4.2)**	**13 (2–28)**	**−16 (−36–4)**

to 2008). Population growth and demand growth is most likely to occur in south-east England, the driest area of the UK. Second, increased population would lead to increased discharges of sewage effluent to treatment works and the water environment, although the effects of this would depend on changes to water treatment practices.

The water environment may also be affected by future changes in land cover and use. Increased urbanisation and a potential increase in the area of land devoted to biofuels may affect river flow regimes and recharge through altering flow and recharge generation processes, but potentially the greatest effect of land use change is on water chemistry. Fertiliser use in the UK is currently declining (Defra, 2014) and overall pesticide use is also declining (although the areas receiving pesticide applications are increasing) (The Food and Environment Research Agency, 2013), but many factors affect pesticide and fertiliser use so it cannot be assumed that current trends will continue and there is a legacy of nutrient pollution which will continue to affect water quality for decades. Changes to farming practices have the potential to alter loads and affect the mechanisms by which material reaches the water course.

III Potential effects of climate change on the water environment

Introduction

Table 4 lists the refereed papers (as of May 2014) which consider explicitly the implications of future climate change for the water environment in the UK, categorised by major pressure. Some of the papers cover several pressures (for example both river flows and nutrients), and some papers consider some pressures en route to estimating impacts on other pressures (for example, whilst there have been few published papers dealing specifically with the effects of future climate change on river water temperature in the UK, most of the studies looking at nutrients and oxygen depletion incorporate potential changes in temperature). The papers do not necessarily represent separate studies (some times different aspects of the same project are reported in several papers), but most include some form of quantitative analysis. The table does not include studies which have examined past associations between variability in weather or climate and the water environment, unless they specifically considered implications for the future. Government and water management agencies have also commissioned and published reports into various aspects of climate change and the water environment.

Table 4. Published papers and reports into the potential effects of future climate change on the water environment in England.

	Rivers	Groundwater	Lakes	Transitional and coastal waters
Volume	Arnell (1992a, 1992b, 2003, 2004, 2011); Arnell and Reynard (1996); Arnell et al. (2014b); Bell et al. (2012); Boorman and Sefton (1997); Calder et al. (2009); Charlton and Arnell (2014); Christierson et al. (2012); Chun et al. (2009); Cloke et al. (2010); Diaz-Nieto and Wilby (2005); Fowler and Kilsby (2007); Fung et al. (2013); Jin et al. (2012); Kay and Jones (2012); Ledbetter et al. (2012); Limbrick et al. (2000); Lopez et al. (2009); New et al. (2007); Pilling and Jones (1999a, 1999b); Prudhomme and Davies (2009a, 2009b); Prudhomme et al. (2003, 2010, 2012, 2013a, 2013b); Remesan et al. (2014); Reynard et al. (2001); Sanderson et al. (2012); Sefton and Boorman (1997); Thompson (2012); Werritty (2002); Wilby (2005, 2006); Wilby and Harris (2006); Wilby et al. (2006a); Environment Agency (2006, 2009); Rance et al. (2012); Reynard et al. (2005, 2009); UKWIR (1997, 2002, 2007)	Bloomfield et al. (2003); Cooper et al. (1995); Herrera-Pantoja and Hiscock (2008); Holman (2006); Holman et al. (2009); Jackson et al. (2011); UKWIR (1997, 2002, 2007)		
Water temperature	Orr et al. (2014); Environment Agency (2007a)		Arvola et al. (2010); George (2007); George et al. (2004, 2007); Jones et al. (2010)	Edwards et al. (2006); Maier et al. (2012); Statham (2012)
Nutrients and eutrophication	Astaraie-Imani et al. (2012); Bouraoui et al. (2002); Crossman et al. (2013); Dunn et al. (2012); Ferrier et al. (1995); Jin et al.	Stuart et al. (2011)	Anderson et al. (2012); Battarbee et al. (2012); Bennion et al. (2012); Blenckner et al. (2010); Carvalho and Kirika (2003); Carvalho et al.	Edwards et al. (2006); Friocourt et al. (2012); Peperzak (2005); Statham (2012)

(continued)

Table 4. (continued)

	Rivers	Groundwater	Lakes	Transitional and coastal waters
	(2012); Whitehead et al. (2006, 2009a, 2009b, 2013); Wilby et al. (2006a); Environment Agency (2008a); ADAS (2004); Hutchins et al. (2013); Rance et al. (2012); UKWIR (2000, 2001, 2006)		(2012); Curtis et al. (2014); Elliott (2012); Elliott et al. (2005, 2006); Elliott and May (2008); George et al. (2010); Howard and Easthope (2002); Jones et al. (2011); Moore et al. (2010); Moss et al. (2011); Thorne and Fenner (2011); Thackeray et al. (2008); Hutchins et al. (2013); UKWIR (2000, 2001)	
Organic enrichment and oxygen depletion	Astaraie-Imani et al. (2012); Cox and Whitehead (2009)		Foley et al. (2012)	
Dissolved organic carbon	Tang et al. (2013); Worrall et al. (2004)		Monteith et al. (2007, 2014)	
Pollutants	Bloomfield et al. (2006); Foulds et al. (2014), Macleod et al. (2012); Curtis et al. (2014); Monteith et al. (2014) UKWIR (2004)	Bloomfield et al. (2006)		
Acidification	Evans et al. (2008); Helliwell and Simpson (2010); Curtis et al. (2014); Monteith et al. (2014)		Battarbee et al. (2014); Curtis et al. (2014); Monteith et al. (2014); Wright et al. (2006)	
Sediments and morphology	Coulthard et al. (2012); Lane et al. (2007); Lewin and Macklin (2010); Macklin and Lewin (2003); Macklin and Rumsby (2007); Mullan (2013); Mullan et al. (2012); Whitehead et al. (2009b)			Karunarathna (2011); Environment Agency (2010)
In-stream habitats	Johnson et al. (2009); Durance and Ormerod (2007, 2009); Gauld et al. (2013); Graham and Harrold (2009), Walsh and Kilsby (2007); Whitehead et al. (2009b); Brown et al. (2012); CEFAS (2004, 2012); Environment Agency (2005a, 2005b, 2007b, 2008b, 2009); Natural England and RSPB (2014)		Elliott and Elliott (2010); Griffiths (2007); Hopkins et al. (2011); Jeppesen et al. (2012); McKee et al. (2002); Winfield et al. (2008a, 2008b, 2010, 2012)	Callaway et al. (2012); Cheung et al. (2012); Fuji and Raffaelli (2008); Goodwin et al. (2013); Hawkins et al. (2009); Heath et al. (2012); Hiscock et al. (2004); Jackson and McIlvenny (2011); Jones et al. (2013); Lee (2001); Nicolas et al. (2011); Rombouts et al. (2012); Pinnegar et al. (2012)

These too are shown in Table 4; note that the list includes some scoping studies. Some of these studies have also been presented in the refereed literature.

Key conclusions from the overview of the literature are:

- very few papers have considered biological aspects of water quality in rivers, with most focused on water chemistry;
- there have been far more papers on surface waters than groundwater;
- there has so far been very little published research on potential changes in sediment properties and river and lake morphology;
- most of the chemical water quality papers concentrate on nitrogen and phosphorus dynamics;
- there is little literature on coastal and transitional waters;
- published studies do not explicitly consider policy-relevant determinands – with the exception of nitrogen and phosphorus;
- virtually all projections of the potential effect of climate change in rivers use models, whilst most of the studies in lakes rely on experimental or observational evidence on sensitivity to change;
- studies have largely focused on a small number of case study catchments or water bodies;
- few studies have so far used the UKCP09 climate projections, with most utilising earlier projections.

Figure 1 presents a conceptual model of the effects of climate change on the water environment, based on the literature shown in Table 4 and first principles. The water environment in a water body is characterised by the quantity of water (and its variation over time), together with its physical, chemical and biological properties that form ecosystems. The two key physical properties are temperature and sediment concentration. The chemical properties are a function of the materials dissolved in the water or present in sediments, and the biological characteristics are defined by the assemblage of plants and animals in the water body and their interaction. There are links between these different components. Chemical, biological and physical characteristics may depend on water temperature, many chemical changes in a water body are driven by microbial processes and both chemical composition and physical properties affect biology.

Climate change affects these four components of the water environment differently but – crucially – all together at the same time, as ecosystems. Changes in weather regimes will affect the volume and timing of river flows, inflows to lakes, transitional waters and the coastal zone and the amount of groundwater recharge. Increases in air temperature affect water temperature and the thermal structure of standing water. Changes in the chemistry of water bodies will be determined by changes in the *sources* of material, *pathways* by which material reaches the water body, and processes within the water body itself – the *receptor*. The biological characteristics of a water body will be affected not only by changes in hydrological, physical and chemical characteristics, but also by changes in habitat suitability, food-web structure and the presence of invasive species. Climate change will be superimposed onto other changes in the catchment. In a given catchment, these land use changes or changes in management practices may be more significant for the water environment than climate change alone (as shown, for example, by Crossman et al., 2013). In the uplands, air pollution and its legacy may remain the dominant control on water quality for many headwaters.

Hydrological changes

Change in the volume and timing of river flows. Many studies (Table 4) have assessed the implications of climate change for river flow

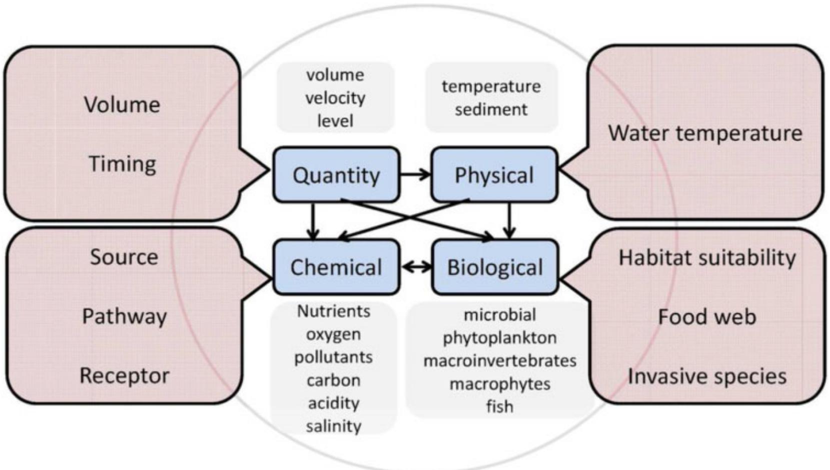

Figure 1. The impact of climate change on the water environment.

regimes in England. All have used catchment hydrological models with several generations of climate scenario; there have so far been few studies of hydrological changes under the UKCP09 projections (Christierson et al., 2012; Kay and Jones, 2012; Charlton and Arnell, 2014). Three key conclusions from the studies in Table 4 are (i) that impacts on river flow regimes may be substantial (with summer flows potentially declining by around 30% by the 2020s: Christierson et al., 2012), (ii) that there is considerable uncertainty in projected impacts, largely due to uncertainty in projected changes in climate as represented by different climate scenarios, and (iii) different types of catchment respond differently to the same climate scenario. There is a clear distinction between the effects of climate change in groundwater-dominated catchments and those with more responsive hydrological regimes, and there is a difference in response between wet upland catchments and drier lowland catchments due to the different baseline water balances. There are of course a number of caveats with these studies. Different hydrological models could produce different changes, although this effect is probably smaller than the considerable range between scenarios. More significantly, most climate scenarios, as currently applied in catchment-scale impact studies, do not explicitly incorporate potential changes in the characteristics of daily rainfall or changes in the year to year variability in rainfall. They may therefore understate the potential effects of climate change on the variability in river flows over time.

Climate change also has the potential to alter river flow generation processes, although this has not yet been assessed in any studies in England. For example, warmer, drier conditions in summer could lead to changes to soil structure (for example cracking), which could change the nature of hydrological response to subsequent rainfall. Such changes are not incorporated into the current generation of hydrological models used to estimate climate change impacts.

Change in groundwater recharge. Ground water in England is typically recharged during winter, when soil moisture deficits are minimal (recharge also can occur in other seasons when soil moisture deficits are eliminated). In general, warmer temperatures will lead to a reduction in the recharge season (starting later and finishing earlier), but this may be exaggerated or offset by changes in seasonal rainfall totals; recharge may therefore either increase or decrease (Herrera-Pantoja and

Hiscock, 2008; Jackson et al., 2011). As with river flow generation, recharge processes may be affected by climate change. During very intense rainfall, or when soils are saturated for prolonged periods, recharge may occur rapidly through 'fast' recharge routes (such as macropores and fissures).

Changes in physical properties

Change in water temperature. River temperature is a key determinant of water quality that affects chemical and biological processes. At low-frequency time-scales, such as monthly, empirical relationships are often used to determine water temperatures from air temperatures (Orr et al., 2014). However, at the time-scale at which biogeochemical processes operate, simple empirical relationships are not appropriate and do not provide any detail of the thermal regime experienced by aquatic organisms. Water and air temperature are not well correlated at a fine temporal scale (Webb et al., 2008) because the thermal regime of the river is affected by factors such as radiation and evaporative heat fluxes, heat transfer to/from the streambed and mixing of groundwater inputs, as well as water management practices (e.g. Caissie et al., 2007; Webb et al., 2008; Williams and Boorman, 2012).

The effects of climate change on lake water temperature profiles depend not only on the change in temperature and energy balance, but also on the characteristics of the lake, including its depth and degree of mixing (Arvola et al., 2010). Higher temperatures and increased emissions of long-wave radiation generally increase lake water temperature at the surface, but stimulate earlier and more persistent stratification so thermal profiles through the lake will change (George et al., 2007). Lake temperature changes are most influenced by changes in winter and night-time air temperatures (Jones et al., 2010). The incidence and length of winter ice cover will diminish.

Sea level rise and saline intrusion. In principle, a rise in sea level could lead to increased saline intrusion into coastal aquifers, although the effect will vary locally depending on factors such as local hydraulic gradients and the amount of abstraction from the aquifer (Ferguson and Gleeson, 2012). Sea level rise will also affect saline intrusion along estuaries, with the extent of the effect depending on local gradients and tidal patterns.

Morphology and sediment. Changes in river flow regimes have the potential to affect patterns of erosion and deposition within river channels, lakes and estuaries. An increased frequency of intense rainfall events could also generate additional sediment loads. There have been many fluvial geomorphology studies showing how erosion and sedimentation have varied over the past in relation to climatic variability (e.g. Lewin and Macklin, 2010; Macklin and Rumsby, 2007), indicating that English rivers are sensitive to climatic change. However, there has so far only been one published quantitative study in England into the potential for river channel response to future climate change (Lane et al., 2007); it showed that changes in sediment delivery to the channel could be more important than changes in hydrological regime. Three studies (Coulthard et al., 2012: Mullan, 2013; Mullan et al., 2012) have demonstrated the increased risk of soil erosion and therefore sediment delivery due to increased frequency of intense rainfall. For lakes, increased erosion leads to increased sediment accumulation rates and the acceleration of hydroseral development, especially in the littoral zone. Within estuaries, changes in river inflows together with changes in sea level may alter patterns of erosion and sedimentation, but again there has been little published research (see Karunarathna, 2011: Uncles et al., 2013).

Implications for pressures on the water environment

Regulation and compliance in the water environment is largely focused around the linked

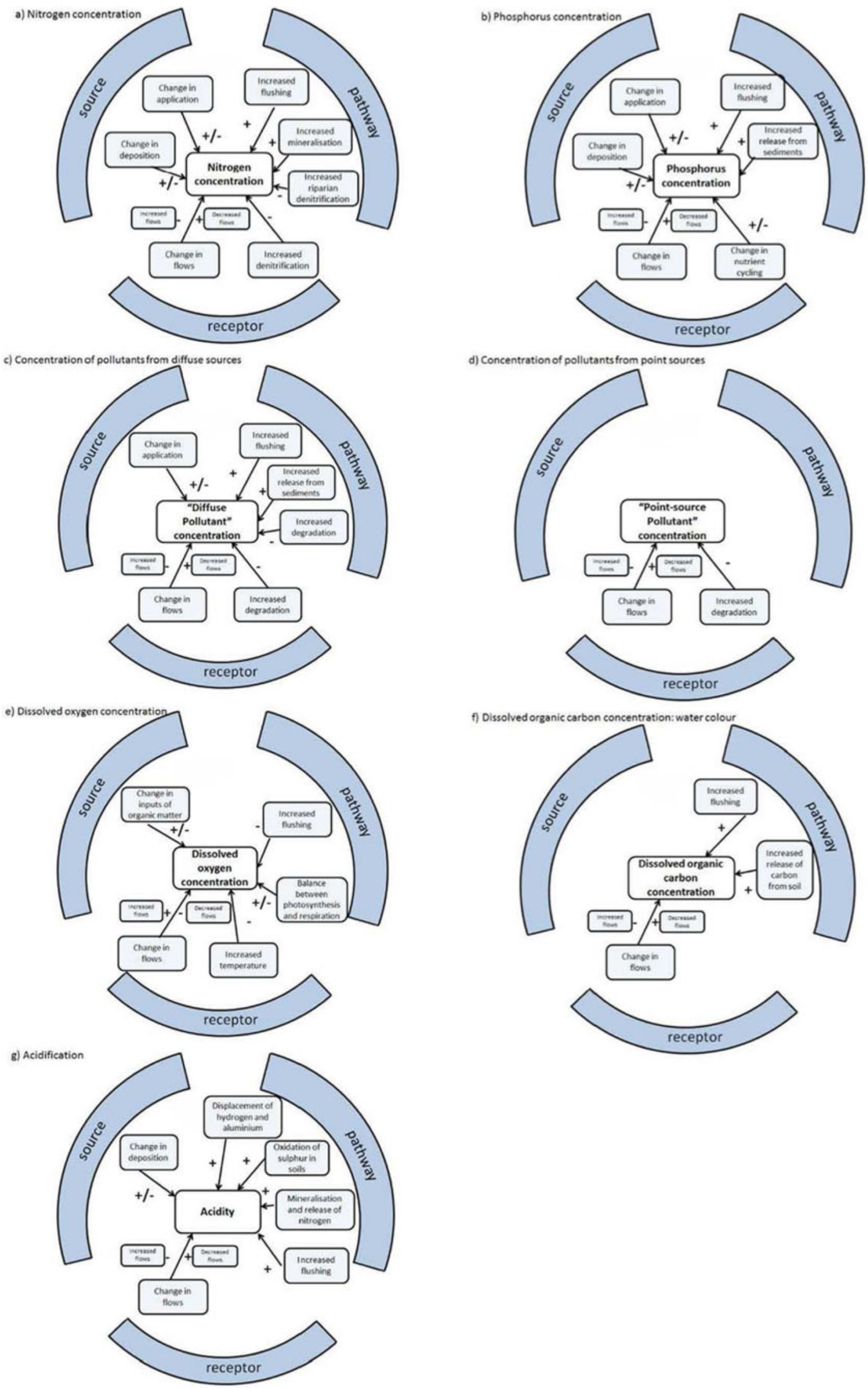

Figure 2. The impact of climate change on pressures on the water environment: sources, pathways and receptors.

chemical and biological characteristics of a water body; a biological 'fail' frequently has a chemical cause. Figure 1 suggests that impacts on chemical characteristics are dependent on changes in sources, pathways and receptors. Figure 2 presents generalised models of the impacts of climate change on chemical characteristics and therefore also biological pressures on the water environment, in terms of changes to sources, pathways and receptors. The models indicate the direction of impact. The magnitude of impact, and the relative importance of the different drivers, will vary with local context (and it is significant that many of the relationships can be either positive or negative); not every change will occur, or be important, everywhere. The models have been developed through a combination of reasoning from first principles and evidence from observational (mostly in lakes) and numerical modelling studies presented in Table 4.

Eutrophication and nutrient enrichment. Eutrophication is the ecosystem response to an excess of nutrients, primarily phosphorus and nitrogen, and it is manifest in increased algal growth, often characterised by blooms of phytoplankton ('algal blooms'), changes in ecosystem structure and function. Climate change has the potential to affect the release of nutrients from catchment soils, the transport of nutrients to water courses, biogeochemical processes within water courses and, via changes in flows, dilution and hence concentrations; it affects sources, pathways and receptors. Figures 2a and 2b present models of the impacts of climate change on the concentrations of the two principal nutrients, nitrogen and phosphorus.

Most nitrogen species come from agricultural land as non-point sources, although drainage from sewage treatment works and septic tanks can make significant contributions in some catchments. In the uplands, high nitrate concentrations in surface waters can be the result of atmospheric deposition and leaching from catchment soils saturated by decades of nitrogen deposition from fossil fuel combustion and agriculture. Changes in precipitation intensity and distribution have the theoretical potential to alter atmospheric deposition rates of pollutant nitrogen. Historically, most phosphorus has come from industrial and domestic sources as point sources from sewage effluent, but with the increasing effluent treatment standards an increasing proportion derives from agricultural land; the balance varies between catchments and the level of effluent treatment. With no change in land use, it is possible that changes in agricultural growing conditions due to climate change could lead to changes – increases or decreases – in the agricultural application of nitrogen and phosphorus to the soil.

Higher soil temperatures and changes in seasonal rainfall and temperature patterns will alter catchment nutrient processing and nitrification in the riparian zone. Changes in the moisture status of the soil are likely to increase mineralisation, leading to increased availability of nitrate for delivery to streams. Increased storm events may also increase the delivery of nutrient loads and sediment from agricultural land through increased flushing, which would mobilise and transport soil particles and associated nutrients to river systems. Increased storm events, especially in summer, could also result in more frequent incidences of combined sewer overflows. These events result in highly polluted water, including untreated sewage, discharging directly into receiving water bodies.

With the projected changes in UK precipitation, it is anticipated that many river systems will see a reduction in summer flows. This would reduce the dilution capacity of system receptors resulting in higher nutrient concentration, particularly in point-source dominated catchments. In addition to reducing receptor dilution capacity, lower summer flows will result in longer water residence times, increasing the potential for eutrophication and the development of algal blooms.

Increased temperatures and lower summer flows may, however, enhance denitrification, potentially lowering riverine nitrogen concentrations, but the effects will depend on the size of the catchment and hence residence times. Changes in nutrient uptake by primary producers (mainly algae) and releases by decomposition may also affect both nitrogen and phosphorus concentrations in water bodies, and a range of chemical phosphorus cycle processes (including direct assimilation, adsorption/desorption and co-precipitation are temperature-dependent). In groundwater-fed catchments, the increased importance of groundwater contributions during low flow periods in the summer could also result in elevated river nitrate concentrations due to historic contamination. In river systems which have experienced historic contamination, remobilisation of within-channel phosphorus has also been observed during storm events, as a result of increased water velocity. In addition, higher temperatures or lower oxygen concentrations in river water may also increase phosphorus release rates from the bed-sediment.

The relative importance of these potential changes to sources, pathways and receptors will vary between catchments. For example, simulations projected increases in summer nitrate concentrations in the River Kennet due to reduced dilution (Whitehead et al., 2006), but reductions in summer nitrate concentrations in the River Thames because increased denitrification offset the reduced dilution effect (Jin et al., 2012).

Altered freshwater fluxes of nutrients, principally nitrogen and phosphorus, will also impact upon estuaries and coastal waters. There is also good evidence (Statham, 2012) that the ratio of nitrogen and phosphorus to silicon has increased in estuaries over time (because of increased anthropogenic loadings of nitrogen and phosphorus), leading to the risk that phytoplankton blooms will consist of potentially toxic cyanobacteria or dinoflagellates rather than diatoms. Submarine groundwater discharges can be important contributors to transitional waters in the UK (e.g. Jickells, 2005), especially for nitrogen. In some areas, depending on the geological setting, there is a large pool of nitrate in groundwater, and climate change-driven hydrological changes leading to a changed flux from this pool may alter considerably nitrogen fluxes into transitional waters.

Increased nutrient loading from upstream as a result of increases in winter precipitation and summer storms would also impact upon eutrophication in lakes, and changes to processes, especially enhanced nutrient recycling within lakes, may further promote eutrophication (Moss et al., 2011). Warmer, drier summers, longer water residence time and earlier and more stable stratification causing reduced hypolimnetic oxygen concentration in deeper, stratifying lakes may lead to increased algal growth (Foley et al., 2012). Phenological change, especially differential earlier growth of some species, may lead to possible mismatches of life-cycles and to complex impacts on lake communities and lake ecosystem functioning. A change in food-web structure and lake functioning caused by rising water temperature can lead potentially to changes in the composition of fish populations and an increase in fish abundance causing increased predation on zooplankton populations and increased algal growth. For shallow lakes, this may also be accompanied by a shift in aquatic plant community composition towards floating plants, dense algal blooms and a decrease in night-time oxygen concentrations, potentially leading to fish kills (Moss et al., 2011).

Pollution from organic contaminants and toxic chemicals. Pollution of water bodies can come from organic contaminants (including microbial contaminants and waterborne pathogens such as faecal indicator organisms (FIOs)) or toxic substances (including heavy metals and persistent organic pollutants (POPs)). These come both from agriculture (from pesticides, fungicides, fertilisers, silage and animals), and

Table 5. Key pollutants affecting compliance with water quality standards.

Category	Primary sources
Nutrients	Agriculture: diffuse Urban: point
Microbial	Agriculture: diffuse Domestic: point
Pesticides and herbicides	Agriculture: diffuse Urban: point
Industrial and domestic chemicals	Industry / urban: point
Transport-derived combustion products	Transport: point, but through drainage system rather than sewage system
Metals	Legacy spoil tips and sediments: diffuse
Endocrine disruptors	Industry / domestic: point
Nano particles	Industry / domestic: point
Pharmaceuticals	Domestic: point Agriculture: diffuse

from a range of industrial, domestic and transport processes. Pollutants are transported along the river network to lakes and estuaries, and can enter the food chain through uptake by benthic invertebrates leading to bioaccumulation in the tissues of fish and shellfish populations; the shellfish waters directive is specifically concerned with this. Table 5 summarises the key types of pollutants that can or could affect compliance with chemical water standards, identifying primary sources and describing whether those sources are point or diffuse. Point and diffuse pollutants will be affected differently by climate change (Figures 2c and 2d).

Total inputs of point-source pollutants (mostly from industry and domestic sources) will be unaffected by climate change, but the application of pesticides and herbicides by farmers may be influenced by the effect of climate change on crop growth. Although the emissions of toxic metals and POPs are now controlled, toxic substances stored in soils and in sediments in the river bed continue to be transported along water courses through leaching and erosion processes. Increased incidences of combined sewer overflows due to more intensive heavy rainfall events could result in highly polluted untreated waters, containing heavy metals and hydrocarbon based pollutants, discharging directly into receiving water bodies (Rügner et al., 2014).

Increased delivery of diffuse pollutants to rivers and groundwater may result from the anticipated changes in extreme events, with storm events resulting in increased flushing and the remobilisation of contaminated materials (Foulds et al., 2014), until the source becomes exhausted. However, higher temperatures will likely increase the volatilisation and degradation of pesticide residues both in the soil and in surface waters, and this will have the effect of reducing pesticide loads (Bloomfield et al., 2006). Changes in runoff generation processes – for example through increased soil cracking – could alter pathways by which pesticides reach water courses and groundwater.

Pollutant concentrations in rivers will also be affected by changes in the volume of river flows. Reductions in summer flows would increase concentrations, whilst higher flows in late autumn, winter and early spring would reduce concentrations; the effect depends on when the pesticides are applied or pollutants discharged. Higher water temperatures may also potentially affect pesticide concentrations in receiving waters through changing degradation rates.

Organic enrichment and oxygen depletion. Reduced dilution effects and increased flushing of organic material from land would increase biochemical oxygen demand (BOD) in rivers and consequently lower dissolved oxygen concentrations (Cox and Whitehead, 2009; Figure 2e). Increased flow velocities due to higher flows would increase reaeration, and lead to increased dissolved oxygen concentrations. Higher water temperature will also reduce the amount of dissolved oxygen in rivers and lakes and as the oxygen depletion rate is more temperature sensitive than the reaeration rate this will also contribute to dissolved oxygen reductions. Dissolved oxygen concentrations will also depend on the balance between photosynthesis and respiration processes in the water body. In addition, algal blooms can exert a significant control over seasonal and diurnal patterns in dissolved oxygen levels and in the hypolimnion of stratifying lakes. The importance of such dynamics may increase under climate change as eutrophication and algal bloom formations become more widespread.

Higher temperatures reduce the water solubility of oxygen and may make stratification in estuaries more intense (Rabalais et al., 2009) which, in conjunction with higher primary productivity and enhanced nutrient inputs, may lead to increased risk of anoxic zones developing. These will have a considerable effect on both organism distribution and biogeochemical cycling.

Dissolved organic carbon. As upland waters recover from the impact of acid deposition, dissolved organic carbon (DOC) concentrations are increasingly affecting the colour of surface waters (Monteith et al., 2007); this colour needs to be removed before water can be supplied to consumers. Higher temperatures may further increase the release of DOC from soil (Figure 2f). The greatest effect of climate change is likely to be through changes in the frequency of short-duration drought events (during which DOC accumulates) followed by heavy rainfall which flushes accumulations to the water course (Tang et al., 2013). Changes in flow would also, of course, affect dilution.

Acidification. Surface water acidification remains a major issue in the UK, particularly within upland systems. However, long-term monitoring under the Upland Waters Monitoring Network (UWMN) is now indicating that almost all monitored streams and lakes are in recovery (Curtis et al., 2014). The impact of climate change on the recovery process is still uncertain but it is possible that pathways in acidified catchments can be significantly affected (Figure 2g). For example, an increased deposition of sea salts due to potentially increased winter storminess would displace hydrogen and aluminium from soil exchange sites, leading to increased acidification. An increased summer drought frequency would lead to increased mineralisation of nitrogen, placing additional acid stress on water courses, and could lead to the oxidation of legacy sulphur retained by anaerobic peaty soils and therefore increased sulphate-dominated acid pulses. As with the other pressures, changes in flow volume will affect dilution.

Overview. There are some common themes across all the pressures. These include the effect of changes in the volume and timing of flows and recharge on the dilution of loads in water bodies (a reduction in flow of 40% increases concentrations by 66.7% with the same load), the likely effect of an increased frequency of flushing events on short-term discharges to water bodies, and the potential effects of changes in the catchment affecting pathways by which material reaches rivers, lakes, coastal waters and groundwater. The relative importance of these different changes will vary between catchments, as will the relative importance of climate and other changes on the water environment.

Implications for habitat suitability and invasive species

Habitats and biodiversity. Water body habitats, and the biodiversity of these habitats, are affected by the pressures outlined above – eutrophication, organic enrichment, pollution, acidification, morphological change (and abstraction of water) – but are also potentially directly affected by changes in the volume and timing of river flows and lake water levels particularly, and by changes in water temperature. Most research in inland waters (Table 4) has concentrated so far on implications for macroinvertebrate communities (e.g. Durance and Ormerod, 2007, 2009) and salmonid fish in rivers (Walsh and Kilsby, 2007) and lakes (e.g. Elliott and Elliott, 2010).

Increasing water temperatures in rivers and lakes may significantly affect freshwater biological assemblages by altering species distributions and abundance through changes in metabolic rates, feeding, migration patterns and physiological harm at different life-cycle stages. Many species, such as salmonid and bullhead species, have thermal limits that determine the success of spawning, migration and survival. Warming could also lead to less suitable conditions for cold and cool-water-adapted species (including high conservation value taxa such as Arctic charr (*Salvelinus alpinus*)), isolating them in increasingly confined headwaters and lakes (Winfield et al., 2008a, 2010). Thermal refuges may be further compromised by oxygen depletion resulting from nutrient enrichment. The thermal tolerances of species can also be lowered by other climatic driven changes in the riverine environment, such as lower water levels and reduced dissolved oxygen concentrations. Other freshwater species, including some macroinvertebrates, can only tolerate a narrow range of temperature, meaning they are highly susceptible to any changes in riverine thermal regime. Reductions in river flows may also restrict access to refugia which aquatic organisms may have historically used, and changes in the river morphology, such as siltation and culverting, may also limit the refugia available.

Temperature increases are likely to impact on the distribution of aquatic plants and animals in transitional and coastal waters (Callaway et al., 2012). Much ecological modelling relating to climate change in coastal waters has focused on water temperature (e.g. Jones et al., 2013; Rombouts et al., 2012). Mobile organisms are likely to move northwards as temperatures rise. The distribution of exploited fish species round the UK is also changing (Nicolas et al., 2011; Heath et al., 2012), with the pattern being consistent with temperature rise. However, it is also clear that patterns of change will be more complex than a simple northerly shift in species, because if keystone species are affected, then there could be widespread changes in community structure and composition. There are likely to be interactions between temperature rise and other driving forces. Marine ecosystems are often dominated by organisms with planktonic life history stages, and are thus sensitive to alterations in coastal circulation patterns. Harmful algal blooms in the North Atlantic and North Sea are potentially affected by changes in circulation, and particularly stratification.

Invasive species. Higher water temperatures and lower flows may result in changes in the distribution and survival of native aquatic organisms, as outlined above. However, these environmental changes will also make the UK aquatic environment increasingly susceptible to the invasion of non-native species or increase in prevalence of existing invasives. The invasion of non-native species is a serious environmental concern as they can have significant detrimental impacts on native species through competition, predation, herbivory, habitat alteration, disease and genetic effects such as hybridisation. For example, the invasion of non-native crayfish species, long-clawed or Turkish crayfish (*Astacus leptodactylus*) and North American signal crayfish (*Pacifastacus leniusculus*), are impacting on native crayfish, white-clawed/Atlantic stream crayfish (*Austropotamobius pallipes*), through competition, and invasion of non-native grass carp (*Ctenopharygdon idella*) is adversely affecting the native macrophyte communities in rivers (Hill et al., 2005).

The potential for invasion varies between water bodies, with the greatest potential in coastal and transitional waters. In inland water bodies, invasive plant species are most likely to be introduced by human action intentionally and unintentionally moving propagules.

IV Implications for water management

The WFD does not explicitly mention climate change in either the setting of standards or the assessment of risks, although the 2009 RBMPs for England (and Wales) do include highly-generalised qualitative assessments of the effects of climate change on pressures on the water environment. Wilby et al. (2006b) identified five potential implications of climate change for the WFD. The first is on the characterisation of water bodies (different standards are applied to different classes), but in practice it is unlikely that climate change will mean that water bodies in England will change character (Environment Agency, 2007c) because characterisation is largely based on geological and physical properties such as size, altitude and exposure.

The second potential implication of climate change (Wilby et al., 2006b) is on the risk of water bodies failing to meet regulatory compliance objectives. Table 1 listed the main regulatory drivers on compliance, and it was noted that in most cases compliance was based on the status of water bodies. Climate change has the potential to alter water body status, and therefore compliance – and the general direction of change is to increase risks of non-compliance with objectives. The evidence from the literature shows that these risks will vary from one catchment or water body to another.

Wilby et al.'s (2006b) third implication of climate change was for the effectiveness of the programmes of measures incorporated within RBMPs to achieve water environment objectives. For example, with higher water temperatures and lower diluting flows, planned improvements to effluent treatment and controls on diffuse pollution might become less effective. In order to maintain compliance, it may therefore be necessary to further develop and implement measures to maintain the quality of water bodies, but a key implication of the literature evidence, again, is that this would depend on local conditions. Whitehead et al. (2006) demonstrated that it was technically feasible to offset through a suite of measures the effects of climate change on nutrient concentrations (and therefore compliance) in a lowland chalk stream, but did not evaluate costs and other barriers. Some of the consequences of climate change (for example the effects of higher water temperature) may be difficult to avoid through adaptations to water management approaches. In such cases, climate change could imply an unavoidable regulatory failure – or that the standards of what is deemed to be 'acceptable' or 'good' would need to be changed.

Wilby et al.'s (2006b) fourth implication of climate change was for monitoring, and in particular for the maintenance of long-term monitoring for trend detection and the selection of reference sites used to define 'good' status. Their final implication was for the river basin planning process under the WFD; climate change adds uncertainty to potential future risks and the effectiveness of response measures, for example, and many land use measures that are being considered to address climate change (for example relating to soil protection, agricultural production and biofuel production) will affect the water environment.

V Conclusions

This review has identified the extent of our understanding of the way climate change might affect a range of dimensions of the water environment in England. There is a large literature on potential impacts (over a 100 papers in the refereed literature), but most studies have looked at flow volumes or nutrients, and none have considered explicitly the implications of climate change for the delivery of water management objectives. Most of the studies in lakes and estuaries have been based on observations made over long periods and have inferred future changes from past climatic variability, whilst most of the studies of changes in flows and nutrients in rivers have used numerical simulation models. Studies have been undertaken in a very small number of locations (catchments, lakes or estuaries), and it is clear that the impacts of climate change will depend on local conditions – including the extent of pressures on the water environment. It is therefore difficult to extrapolate from the catchment to the national scale for an overall assessment of the implications of climate change for the water environment and compliance with regulatory objectives. Nevertheless, it is possible to conclude that climate change has the potential to pose risks to water management, in two main ways: it affects the status of water bodies (and therefore compliance), and it affects the effectiveness of catchment and in-stream measures to manage the water environment and meet policy objectives. However, the magnitude of this risk depends on local conditions. The interpretation, measurement and definition of WFD status is also potentially affected by a changing climate.

The impact of climate change on the water environment – and therefore the risks posed to water management – is uncertain, for five reasons. First, future changes in relevant aspects of weather and climate are uncertain, and may not be represented in current generation climate scenarios. Changes in most chemical determinands (and therefore biological systems), for example, are strongly dependent on changes in the duration of dry spells and frequency of intense 'flushing' events. Second, whilst there is a good qualitative understanding of potential ways in which systems may change, some of the interactions between components of the water environment are poorly understood and new high-frequency observations are giving new insights into system dynamics (Wade et al., 2012). Third, predictive models are currently only available for some components of the water environment, and these models have parametric and structural uncertainty which has not yet been fully explored. Fourth, climate change is not the only pressure affecting catchments, and how climate change affects the water environment in a place will depend on other land use and management pressures. Finally, the future consequences of climate change will depend on the management actions taken to respond not only to climate change, but also to the other evolving pressures.

The paper has also developed a series of consistent conceptual models describing the implications of climate change for pressures on the water environment, based around the source-pathway-receptor concept. The models have been largely constructed from first principles, but have been informed by the results of observational and modelling studies. They provide a framework for a systematic assessment across catchments and pressures of the implications of climate change for the water environment and its management.

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